Measuring the Mass of the Lightest Chargino at the CERN LHC

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Abstract

Results are presented of a feasibility study of techniques for measuring the mass of the lightest chargino at the CERN LHC. These results suggest that for one particular mSUGRA model a statistically significant chargino signal can be identified and the chargino mass reconstructed with a precision $\sim 11\%$ for ~ 100 fb^{-1} of data.

1. INTRODUCTION

Much work has been carried out recently on measurement of the masses of SUSY particles at the LHC [1, 2, 3, 4, 5, 6]. These measurements can often be considered to be 'model-independent' in the sense that they require only that a particular SUSY decay chain exists with an observable branching ratio. A good starting point is often provided by the observation of an opposite-sign same-flavour (OS-SF) dilepton invariant mass spectrum end-point whose position measures a combination of the masses of the $\tilde{\chi}_2^0$, the $\tilde{\chi}_1^0$ and possibly also the $\tilde{l}^{\pm}$. Observation of end-points and thresholds in invariant mass combinations of some or all of these leptons with additional jets then provides additional mass constraints sufficient to allow the individual sparticle masses to be reconstructed unambiguously. A question remains however regarding how the mass of a SUSY particle can be measured if it does not participate in a decay chain producing an OS-SF dilepton signature. This problem has been addressed for some sparticles (e.g. for the $\tilde{q}_R$ [7]) however significant exceptions remain. Notable among these is the case of the lightest chargino $\tilde{\chi}_1^{\pm}$, which does not usually participate in decay chains producing OS-SF dileptons due to its similarity in mass to the $\tilde{\chi}_2^0$.

In this paper we attempt to measure the mass of the $\tilde{\chi}_1^{\pm}$ by identifying the usual OS-SF dilepton invariant mass end-point arising from the decay via $\tilde{\chi}_2^0$ of the *other* initially produced SUSY particle (i.e. not the one which decays to produce the $\tilde{\chi}_1^{\pm}$). We then solve the mass constraints for that decay chain to reconstruct the momentum of the $\tilde{\chi}_1^0$ appearing at the end of the chain, and use this to constrain the momentum (via E_T^{miss}) of the $\tilde{\chi}_1^0$ appearing at the end of the decay chain involving the $\tilde{\chi}_1^{\pm}$. We finally use mass constraints provided by additional jets generated by this chain to solve for the $\tilde{\chi}_1^{\pm}$ mass. The technique requires that both the decay chain

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R l q \to \tilde{\chi}_1^0 l l q$$

and the decay chain

$$\tilde{q}_L \to \tilde{\chi}_1^{\pm} q \to q W^{\pm} \tilde{\chi}_1^0 \to q q' q'' \tilde{\chi}_1^0$$

are open with significant branching ratios, and that the masses of the $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{l}_R$ and $\tilde{q}_L$ are known. No other model-dependent assumptions are required however.

2. SUSY MODEL AND EVENT GENERATION

The SUSY model point chosen was that used recently by ATLAS for full simulation studies of SUSY mass reconstruction [8]. This is a minimal Supergravity (mSUGRA) model with parameters $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan(\beta) = 6$ and $\mu > 0$. The mass of the lightest chargino is

218 GeV, while those of the $\tilde{q}_L$, the $\tilde{l}_R$, the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ are ~ 630 GeV, 155 GeV, 218 GeV and 118 GeV respectively. One of the characteristics of this model is that the branching ratio of $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ is relatively large (~ 28 %). Chargino mass reconstruction involving the decay $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1 \nu_\tau$ (BR ~ 68 %) is likely to be very difficult due to the additional degress of freedom provided by the missing neutrino. Consequently the $W^\pm$ decay mode must be used.

The electroweak SUSY parameters were calculated using the ISASUGRA 7.51 RGE code [9]. SUSY events equivalent to an integrated luminosity of 100 fb^{-1} were then generated using Herwig 6.4 [10, 11] interfaced to the ATLAS fast detector simulation ATLFAST 2.21 [12]. With the standard SUSY selection cuts described below Standard Model backgrounds are expected to be negligible. An event pre-selection requiring at least two ATLFAST-identified isolated leptons was applied in order to reduce the total volume of data.

3. CHARGINO MASS RECONSTRUCTION

Events were required to satisfy 'standard' SUSY selection criteria requiring a high multiplicity of high p_T jets, large E_T^{miss} and multiple leptons:

- at least 4 jets (default ATLFAST definition [12]) with $p_T > 10$ GeV, two of which must have $p_T > 100$ GeV,
- $\left(\sum_{i=1}^{4} p_{T(jet)}^i + E_T^{miss}\right) > 400$ GeV,
- $E_T^{miss} > \max\left(100\text{GeV}, 0.2\left(\sum_{i=1}^{4} p_{T(jet)}^i + E_T^{miss}\right)\right)$,
- exactly 2 opposite sign same flavour isolated electrons or muons with $p_T > 10$ GeV,
- no b-jets or τ-jets.

Events were further required to contain dileptons with an invariant mass less than the expected $l^\pm l^\mp$ end-point position (100.2 GeV) and at least one dilepton + hard jet combination (one for each combination of the dilepton pair with each of the two hardest jets) with an invariant mass less than the expected $l^\pm l^\mp q$ end-point position (501.0 GeV). The smaller dilepton + hard jet combination then defined which jet (assumed to be from the decay $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q$) would be used together with the dileptons to reconstruct the $\tilde{\chi}_2^0$ production and decay chain.

The momentum of the $\tilde{\chi}_1^0$ at the end of the $\tilde{\chi}_2^0$ decay chain was calculated by solving analytically the kinematic equations relating the momenta of the decay products (including the $\tilde{\chi}_1^0$) to the masses of the SUSY particles, which were assumed to be known from conventional end-point measurements [1, 2, 3, 4, 5, 6]. This process is described in more detail in Ref. [13] and results in two solutions for the $\tilde{\chi}_1^0$ momentum for each of the two possible mappings of the reconstructed leptons to the sparticle decay products. In the present analysis just one such mapping was assumed with no attempt being made to select the correct assignment. Two possible solutions for the $\tilde{\chi}_1^0$ momentum were therefore obtained for each event.

The nest step in the reconstruction was to find the jet pair resulting from a hadronic $W^\pm$ decay following production via $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$. The potentially large combinatorial background was reduced by rejecting jet combinations involving either of the two hardest jets (since these were assumed to arise from $\tilde{q}_L$ decay) and by requiring that the harder(smaller) of the two jets possessed p_T greater than 40(20) GeV (i.e. selecting asymmetric jet pairs consistent with a significant boost in the lab frame). A further cut was applied on the invariant mass of the combination of the jet pair with the hard jet giving the larger dilepton + jet mass (assumed therefore to be the jet from the $\tilde{q}_L \rightarrow \tilde{\chi}_1^\pm q$ decay preocess). This invariant mass was conservatively required to be less than that of the $\tilde{q}_L$.

For each event any jet pairs satisfying the above criteria and possessing $|m_{jj} - m_W| < 15$ GeV (Fig. 1), were considered to form W candidates. For each event the candidate with m_{jj} nearest m_W was then selected and used together with the momentum of the hard jet identified previously and the two assumed x and y components of the $\tilde{\chi}_1^0$ momentum (calculated from the two solutions for the momentum
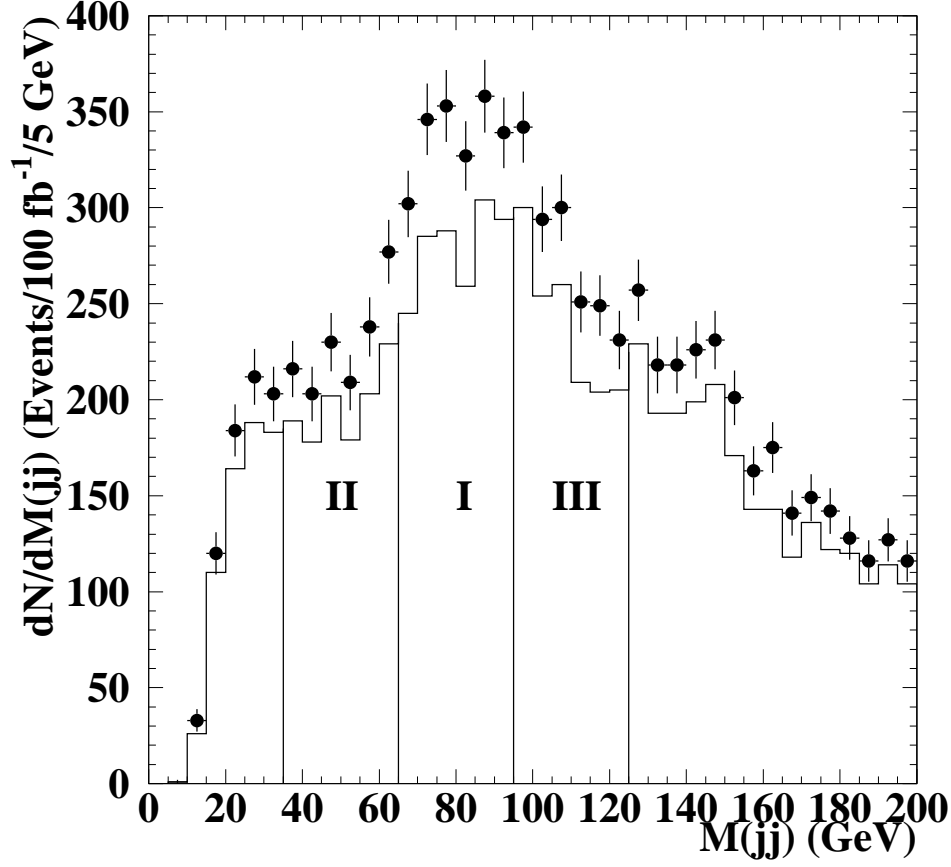
Fig. 1: *Reconstructed dijet invariant mass distributions for all events (data points) and events not containing the decay chain* $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to q'q''\tilde{\chi}_1^0$ *selected using Monte Carlo truth. The signal band is labelled 'I' in the figure, while the two sideband are labelled 'II' and 'III' respectively.*

of the $\tilde{\chi}_1^0$ from the $\tilde{\chi}_2^0$ decay and E_T^{miss}) to calculate the chargino mass. Each of the two solutions for the $\tilde{\chi}_1^0$ momentum gives two possible solutions for $m_{\tilde{\chi}_1^{\pm}}$, the smaller of which is usually physical. Consequently two possible values for $m_{\tilde{\chi}_1^{\pm}}$ were obtained from each event (plotted in Fig. 2).

Following this procedure significant backgrounds remain from combinatorics in SUSY signal events (due to their high average multiplicity), and from SUSY background events (i.e. events in which the decay process $\tilde{q}_L \to \tilde{\chi}_1^{\pm}q \to qW^{\pm}\tilde{\chi}_1^0 \to qq'q''\tilde{\chi}_1^0$ is not present). These backgrounds (or at least those not involving a real $W^{\pm}$ decay) were removed statistically using a sideband subtraction technique similar to that described in Ref. [14]. All jet pairs satisfying all the above selection criteria except the $|m_{jj} - m_W|$ requirement were recorded if they satisfied the alternative requirement that 15 GeV $<$ $|m_{jj} - m_W| < 45$ GeV. This requirement then defined two side-bands located on either side of the main signal band ($|m_{jj} - m_W| < 15$ GeV) of equal width 30 GeV. The momentum of each jet pair was then rescaled such that the difference between its rescaled mass and m_W was the same as the difference between its original mass and the centre of its sideband (50 or 110 GeV respectively). Each jet pair was then given a weight of 1.3 (lower sideband) or 1.0 (upper sideband) to account for the variation of the background m_{jj} distribution with m_{jj} (Fig. 1). Values for the chargino mass were then calculated for each jet pair and used to create a sideband mass distribution (Fig. 2). Finally the sideband mass distribution was subtracted from the signal mass distribution with a relative normalisation factor of 0.7 to
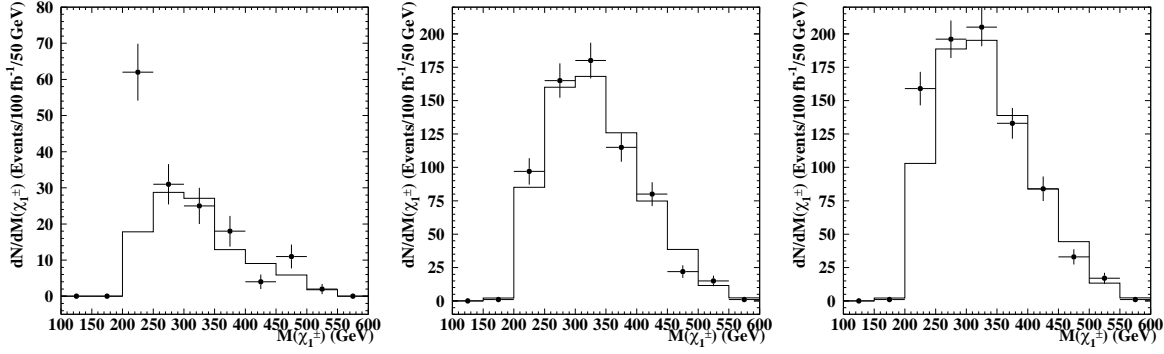
Fig. 2: *Reconstructed $\tilde{\chi}_1^{\pm}$ mass distributions showing signal distributions with $|m_{jj} - m_W| < 15$ GeV (data points) and sideband distributions with 15 GeV $< |m_{jj} - m_W| < 45$ GeV (histograms). The left hand figure was obtained by selecting events containing the decay chain $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to q'q''\tilde{\chi}_1^0$ using Monte Carlo truth. The central figure was obtained by selecting background events not containing this decay chain. The right hand figure was obtained by using all data.*

account for the differing efficiencies for selecting sideband events and background events in the signal region.

4. RESULTS

The sideband subtracted chargino mass distributions obtained from this process are shown in Fig. 3, both with and without a selection requirement for $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to q'q''\tilde{\chi}_1^0$ obtained from Monte Carlo truth. In both cases no events are observed at masses below the kinematic limit of 198 GeV ($= m_W + m_{\tilde{\chi}_1^0}$) due to the origin of the mass values as solutions to the kinematic mass relations. In the case where Monte Carlo truth was used as input a clear peak is seen in the 200 GeV - 250 GeV bin, corresponding well to the actual mass of 218 GeV. At higher mass values the sideband subtraction process has worked well and the distribution is consistent with zero. In the case where no Monte Carlo truth signal event selection has been performed (points with errors) a clear peak is again seen in the vicinity of the chargino mass, with few events at higher values. For 100 fb^{-1} the statistical significance of the peak is around 3 σ indicating that more integrated luminosity (or an improved event selection) would be required to claim a 5 σ discovery. Nevertheless it seems reasonable to claim that if this data were generated by an LHC experiment such as ATLAS, and that the observed signal were indeed not a statistical fluctuation, then the mass of the lightest chargino could be measured to a statistical precision $\sim \pm 25$ GeV (~ 11 %). More work is needed to determine the likely systematic error in this quantity arising from effects such as the statistical and systematic uncertainty in the input sparticle masses used when calculating the $\tilde{\chi}_1^0$ momentum and $\tilde{\chi}_1^{\pm}$ mass.

More work is needed to identify the optimum set of selection criteria required to identify hadronic $W^{\pm}$ decays in this sample, with the efficiency of the tau veto (required to remove $\tilde{\chi}_1^{\pm}$ decays via $\tilde{\tau}_1 \nu_{\tau}$) in particular needing to be optimised. Possible methods for selecting the correct lepton mapping used to calculate the $\tilde{\chi}_1^0$ momentum also deserve further study. With these improvements and/or more integrated luminosity it should then be possible both to increase the accuracy of the chargino mass measurement and to study quantities such as the helicity of the $\tilde{\chi}_1^{\pm}$ through measurement of the invariant mass distribution of the $W^{\pm}$ and the hard jet produced alongside the $\tilde{\chi}_1^{\pm}$ in the decay of the parent $\tilde{q}_L$.

5. CONCLUSIONS

A study of the identification and measurement of charginos decaying to $W^{\pm}\tilde{\chi}_1^0$ produced at the LHC has been performed. The results indicate that for one particular mSUGRA model the mass of the $\tilde{\chi}_1^{\pm}$ can be
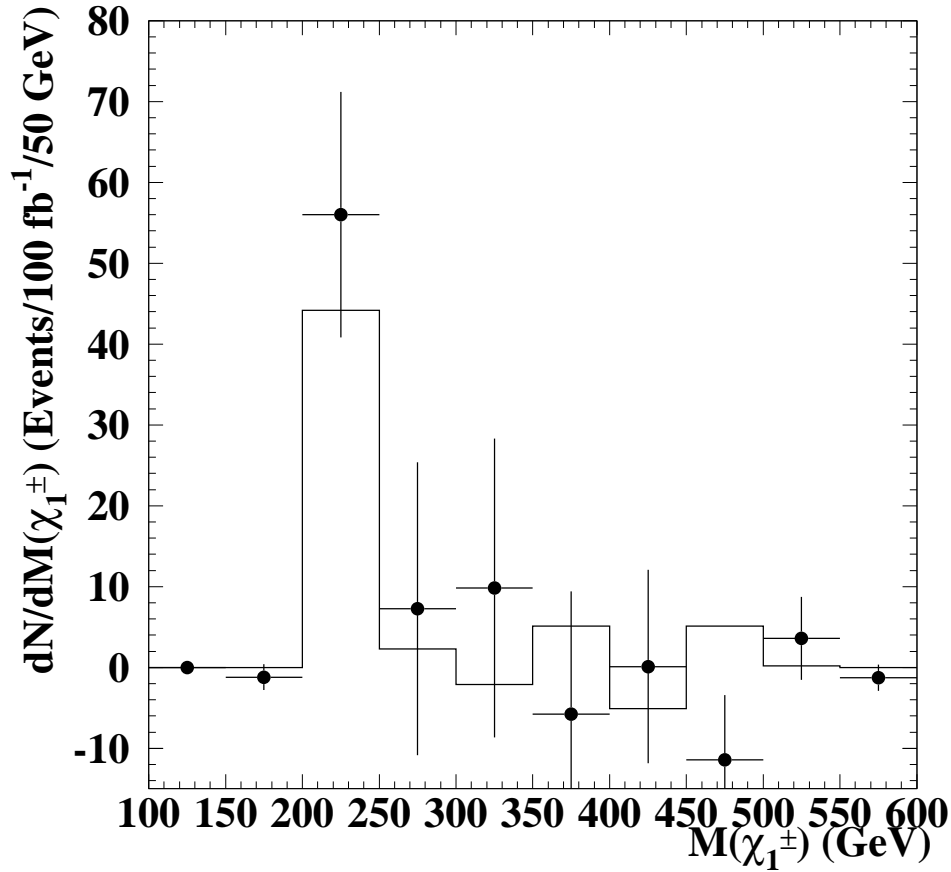
Fig. 3: *Reconstructed $\tilde{\chi}_1^{\pm}$ mass distribution for $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to q'q''\tilde{\chi}_1^0$ signal events (histogram) and all events (points with errors).*

measured with a statistical precision ~ 11 % for 100 fb^{-1} of integrated luminosity.

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